BLURRING THE LINES: AN INTEGRATED COMPOSITIONAL MODEL FOR DIGITAL MUSIC INSTRUMENT DESIGN

Mat Dalgleish[1], Chris Foster[1], Steve Spencer[1]

[1]*University of Wolverhampton*

Correspondence should be addressed to: m.dalgleish2@wlv.ac.uk

Abstract: **Computer-based interactive music systems date back as far as the late 1960s, but increasingly accessible technologies have prompted significant growth in interest in digital musical instruments (DMIs) over the last decade. To date, the designers of DMIs have generally borrowed paradigms from acoustic instruments or the field of Human-Computer Interaction (HCI). However, it can be argued that DMIs are a fundamentally different case and the suitability of these paradigms is debatable at best. For instance, DMIs lack the haptic feedback of acoustic instruments. Musical instruments are also highly specialized rather than general-purpose tools, and musical performance is not typically task-based. Additionally, Jordà notes that their designers have tended to focus on isolated parts of the problem, to the detriment of instrumental cohesion and character. While a few authors have considered DMIs as more fully rounded constructions, and the term 'composed instruments' has been used to describe the specification of the input-output relationship as an intentional act of composition, we argue that this is insufficient. Drawing on theories of affordances and ecological music creation, we describe an alternative model that considers DMI design as part of a broader compositional process that also includes text and hybrid acoustic-digital space. The traditionally distinct roles of designer, composer and performer are seen to blur, and the notion of composition-specific instruments is discussed. As an example of the model in practice, the interdisciplinary collaborative piece *Desire Lines* is described. This serves to aid an initial assessment of the model and its implementation, and informs some remarks around its limitations and future possibilities.**

1. INTRODUCTION

The prevailing view of electronic and computer music has been acoustic-centric, with the traditional keyboard interface an especially recurrent theme. We describe how these models have been maintained, their limitations, and some means of conceptual escape, before moving on to propose a new model that blurs distinctions between design, composition and performance.

1.1. Early Innovations and the Return to the Familiar

While the likes of the Jesuit priest Jean Delaborde had conducted musical experiments with static electricity in the mid-18th century, it was not until the industrialization of electricity at the end of the 19th century that electronic musical instruments arrived in earnest [1][2]. Often influenced by contemporary communication technologies, a number of novel instrument designs were proposed in the early 20th century [3][4]. While some instruments adopted the familiar keyboard interface, the likes of the *Theremin* (1919), *Ondes Martenot* (1928), and *Trautonium* (1928) attempted to match novel means of sound production to equally innovative performer-instrument interaction. However, the period immediately before World War II saw a concerted and sustained return to the keyboard, and a spate of new electronic keyboard instruments such as the *Rangertone Organ* (1932), *Emicon* (1932), *Hammond Organ* (1935), and *Neo Bechstein Piano* (1939) [5].

1.2. Modularity and Beyond

The Post War years saw the rise of the electronic music studio in Europe, the US and beyond. However, timbral limitations meant that electronic instruments were not widely used, at least initially. Instead, two different and initially distinct approaches emerged. The Club d 'Essai de la Radiodiffusion-Télévision Française (RTF) in Paris used recorded and processed acoustic sounds. By contrast, the Westdeutscher Rundfunk Köln (WDR) in Cologne relied on synthetic sounds generated by repurposed broadcast test equipment. For all their conceptual and pragmatic differences, both methods were slow and laborious, hindered by interfaces that drew more from the laboratory than from musical instruments. Thus began the search for technologies that could not only produce similarly complex sounds, but marry this capacity to real-time control.

The development of the modular synthesizer represented a significant step forward. It could generate complex sounds in real-time, and also be quickly and intuitively reconfigured (i.e. programmed) by the user. The first fully patchable modular synthesizer is usually considered to be the *Audio System Synthesizer* (1960) developed by Harald Bode. This was also the first piece of music technology to implement voltage control. In principle at least, any module could be connected to and control any other. Bode's concepts were refined by Robert Moog in the early 1960s. The resultant *Moog Modular* (1964) was primarily aimed at professional musicians and adopted a conventional keyboard as its performance interface. On the opposite coast of the US and apparently unaware of Moog, Donald Buchla had developed a rival modular synthesizer design. Instead of a musical instrument per se, Buchla considered the *100 Series Electronic Music Box* (1964) a kind of experimental sound laboratory. Thus, in place of a conventional keyboard, it offered individually tunable touch-plates and a simple form of sequencer [3] [6].

By 1969, Moog had concluded that his Modular was too complicated and expensive for many professional musicians. The *Minimoog Model D* was released in summer 1970. A smaller, more portable instrument, it distilled the essence of the Moog Modular into a simpler, non-modular form. If much of the flexibility of its predecessor was lost, the familiar keyboard interface remained. As the first commercially successful synthesizer, the Model D remained in production until 1981 and sold around 40,000 units [7]. This success served to reinforce the keyboard-synthesizer paradigm in the minds of users and designers alike.

1.3. Real-Time Computer Music

By the late 1960s, the analog synthesizer had evolved into a capable real-time instrument. However, technological limitations were such that computer music remained an arduous, inherently non-real-time business [3]. The American composer Paul Lansky [8] recalls some of the difficulties of the period:

> Imagine, first of all, you programmed everything on punchcards, then you submitted it and came back the next day, because the computer only ran one job at a time, and sometimes it would take hours and hours just to do anything at all.

One of the earliest attempts at a more performative kind of computer music was the *GROOVE* system developed by Mathews and Moore at AT&T Bell Labs [9]. This hybrid of digital control and analog sound generation adopted the metaphor of the orchestral conductor. Hunt [3] is critical of this conceptual model on the basis that it hands primary control over to the computer, and relegates the influence of the performer to secondary parameters only.

As computers became simultaneously more capable and accessible, a modest number of composers and performers started to develop new interfaces for computer music. These took a variety of forms, from the tablet-based *Unité Polyagogique Informatique CEMAMu* (UPIC) system [10] and the wearable *The Hands* instrument [11] to the spatial topologies of *SOUND=SPACE* [12]. However, these innovations had only limited impact on the mainstream. Instead, the widespread adoption of MIDI [3], a communication protocol designed around the keyboard interface, propagated the keyboard by association, thereby cementing its place in the computer domain like the synthesizer domain before it. To the present day, the plastic MIDI keyboard remains a ubiquitous presence in bedrooms, project studios and education labs [13].

1.4. Freedom and its Discontents

Despite its popularity, the suitability of the keyboard for the digital domain is questionable at best. Digital musical instruments (DMIs) are in many respects a fundamentally different proposition to their acoustic predecessors. For instance, in order to produce sound, acoustic instruments require the performance interface to physically act upon the sound generation mechanism (i.e. they require physical activation). This connection imposes significant constraints on instrument design, but at the same time provides the performer with rich haptic feedback [14]. For Rebelo [15], this haptic sensation plays an important role in the attachment of musicians to their instruments. By contrast, the designers of DMIs are afforded an unprecedented amount of freedom. Sensor technologies enable almost any physical stimuli to be used as input. Similarly, digital sound generation techniques are so numerous that essentially any imaginable sound can be created. Moreover, these two aspects are not inherently co-dependent. Thus, they may be chosen independently, and the relationship between them specified by the designer. However, this connection between input and output is no longer physical. It exists instead only in software. The result is a brutal and emphatic loss of haptic feedback and tactile sensation [15]. For Cook [16] and Trueman [17], this loss is compounded by the tendency to place the loudspeaker outside the body of the instrument.

More radical models that transcend or openly reject the acoustic instrument paradigm have been explored within the New Interfaces for Musical Expression (NIME) community. These include easy to use and intuitive sound toys [18], musical robotics [19], and David Tudor-inspired homemade electronics [20]. Another prominent strand of activity within the NIME community has been the application of tools from the Human-Computer Interaction (HCI) field to the DMI domain [3] [21]. However, it is necessary to remember that musical instruments are highly specialized rather than general-purpose tools, and musical performance is not typically task-based. Furthermore, just as digital audio researchers focus on sound output, the very premise of HCI is that it is heavily focused on input and the interface. For Jordà [21], this tendency to focus on isolated parts of the DMI problem has not only slowed progress in the field, but also had substantial detrimental effect on the development of a distinctive and cohesive instrumental character. The suggestion is that, by considering DMIs as a series of barely-related and interchangeable parts, they are doomed to be flexible but forgettable chimeras, with few consistent traits by which to remember them.

2. Towards an Integrated Composition Model for Digital Musical Instrument Design

In constructing a new model of DMI design we draw on two bodies of theory: ecological thinking in music and affordances.

2.1. From Composed Instruments to Musical Ecologies

A number of authors have attempted to develop more rounded DMI identifies [22] [13] [23]. While in some quarters this has nurtured a desire to revisit and reinstate the acoustic instrument paradigm, the notion of 'composed instruments' offers an alternative route that is arguably less subject to and bound by cultural expectation. In the DMI domain, Wanderley *et al.* [24] use the term in relation to *ESCHER*; a real-time sound synthesis environment developed in jMax. Similar to the one considered problematic by Jordà [21], they describe a model in which the performance interface is considered independently from the sound synthesis algorithm. The potential for composition is situated in the ability to design (or in other words compose) the intermediary connection between the two elements. This may include multiple sequential layers of mapping and vary considerably in shape. The definition of composed instruments offered by Schnell and Battier [2002] is similar in that it too considers the various constituent parts of a DMI to be separate from each other:

> A composed instrument is one in which several conditions must be met. One of them is that the two main components of a musical instrument, the sound producing part and the gestural performance part, are decoupled, or isolated one from another. In a composed instrument, gesture is linked to sound production in a non-direct, oftentimes non-obvious fashion.

However, if discussion of mapping types in the first definition [24] is limited to models based on conventional instruments, Schnell and Battier [25] additionally note that while the adoption of traditional instrumental metaphors is implied, a wide variety of non-musical metaphors may also be implemented.

For Cook [16], creating the input and output ends of the instrument separately and then relying on mapping to bridge the two ex post facto is insufficient, and particularly detrimental to instrumental feel. In an attempt to close the gap between performance interface and sound generation algorithm (and thereby produce more tightly coupled systems), he proposes the notion of co-design. This involves the development of both ends of the instrument simultaneously so that their mutual influence can be more readily considered. The co-design model is also notable in that it extends beyond the interface-mapping-sound generation construction to also consider sound projection/sound diffusion. Cook is thus one of relatively few DMI designers to conceive of this aspect as an integrated part of the instrument.

Others have blurred the line between instrument design and more conventional musical composition. The earliest of these moves pre-date the digital era, and a broad spectrum of approaches have been proposed. At one end of this spectrum are instruments created for specific compositions (i.e. composition-specific instruments). The idiosyncratic acoustic instruments of Harry Partch are perhaps the best-known historical examples of these. While Partch occasionally used conventional instruments, his compositions were often built around specific unconventional scales that divided the octave into unequal intervals (i.e. exploration of different non-standard tunings as a basis for composition). Thus, to realize these ideas, he was often required to produce new instruments on a composition-by-composition basis [26]. Momeni [27] proposes a similar model in the digital domain, and his Ph.D. thesis presents a series of instruments created for specific audiovisual performances. However, in both cases the distinction between instrument and composition is maintained and left intact; the instrument is effectively a specialized product of the composition.

At the other end of the spectrum is the notion of the instrument-composition, or, more descriptively, instrument-as-composition. For Holzer, the possibility that an instrument can itself be a composition is rooted in Cagean thought [28]. He suggests that:

> [….] it is precisely Cage's reformulation of the concert score from a list of deterministic note values to a set of indeterministic possibilities that allowed the blurring of lines between instrument-builder and music composer that followed. [….] in creating electronic music instruments, the builder is in fact simultaneously acting as post-Cagean composer by simultaneously constructing a highly restrictive collection of limitations and an indeterministic set of performance possibilities, each full of as much potential and risk as the builder/composer wishes to allow the performer.

These ideas were first made concrete by the virtuoso pianist-interpreter and Cage collaborator David Tudor. Withdrawing from the piano in the mid-1960s to focus on the creation and performance of live electronic music, Tudor constructed homemade circuits that could be connected together to create pseudo-modular networks. The performance of these electronic circuits departed from convention in that it did not follow a traditional score. Musical performance was instead recast as an exploratory process that revealed or made audible the internal structures of a specific musical system. An eloquent metaphor for this shift is offered by David Berhman [29], that "everything done with a surfboard in the surf is a part of surfing."

If these internal structures are considered in compositional terms; in other words as a set of musical possibilities or affordances grouped in space that may be revealed by the performer over an indeterminate period of time, the schematic of the circuit can therefore be considered the score.

With Tudor's *Rainforest IV* (1973), the instrument-composition was expanded to an architectural scale and recast as a participatory performance environment [30]. More specifically, it is an example of an instrument-composition as a complex ecology of interdependencies between people and sound-objects in space. Furthermore, these interdependencies are present in both the creation and presentation of the piece. First, a small group of composers must each construct several transducer-equipped sculptures. These sculptures are then suspended in the performance space and used to diffuse user-created sound material, thereby highlighting their particular acoustic properties. At the same time, the audience can freely traverse the performance space. Their position within the space and proximity to particular sound sculptures not only determines their individual experience, but also has the potential to influence the broader acoustic ecology.

Beyond the biological sciences, an ecology usually refers to the study of complex relationships between agents and their environment [31]. Ecological approaches are well established in related fields such as HCI [32] [33]. Indeed, Gehlhaar [34] suggests that ecological experience may have become integral to the lives of digital natives:

> The young have also become accustomed to perceptive multi-tasking, to spreading their attention over several layers of experience at the same time. In art, it corresponds to the alliance of several media in order to create either a mutually supporting relationship or an immersive environment. The music provides only one layer of the experience; loosely related visuals, talking and ingesting various stimulants provide the other layers.

The notion of music-specific ecologies has received attention over the last 10-15 years. For instance, in relation to musical Artificial Intelligence (AI), Impett [35] suggests that:

> *Music is understood as a dynamical complex of interacting situated embodied behaviours. These behaviours may be physical or virtual, composed or emergent, or of a time scale such that they figure as constraints or constructs. All interact in the same space by a process of mutual modelling, redescription, and emergent restructuring.*

With a focus on expression, Gurevich and Treviño [31] observe that the dominant model of music creation assumes a unidirectional flow from the creator, to the interpreter, to the listener, and also that expression can be understood as a process of deviation from a text. Arguing against the suitability and adoption of this monolithic model in the DMI domain, they propose an ecological approach based around the "relationships between composers, performers and listeners as a part of a system that includes external factors such as genre, historical reception, sonic context and performance scenario."

If these accounts are human-centric, it is also possible to conceive of acoustic ecologies. Indeed, the diffuseness of sound and its ability to permeate physical barriers may particularly lend itself to this model. For Grimshaw [36], an acoustic ecology is able to span physical and virtual space. It is therefore able to encompass, for instance, the virtual world of a video game and simultaneous input from multiple internet-connected players distributed around the world. His observation that an acoustic ecology is not fixed but in a constant state of flux is also prescient:

> It is constantly changing as players respond to sounds from other players (or computer-generated characters) with their own actions, thereby contributing additional sounds to the acoustic ecology and potentially providing new meaning to, and eliciting further responses from, other players.

The ecological model developed and presented here essentially hybridizes those proposed by Gurevich and Treviño [31] and Grimshaw [36] respectively. While an eology is an inherently slippery and multi-tiered thing that is hard to capture, at the very least it includes the relationships between:

- composers, performers and audience
- sounds and space (real and virtual)
- wider cultural and social influences

A generalized outline of its structure can be seen below (Figure 1).

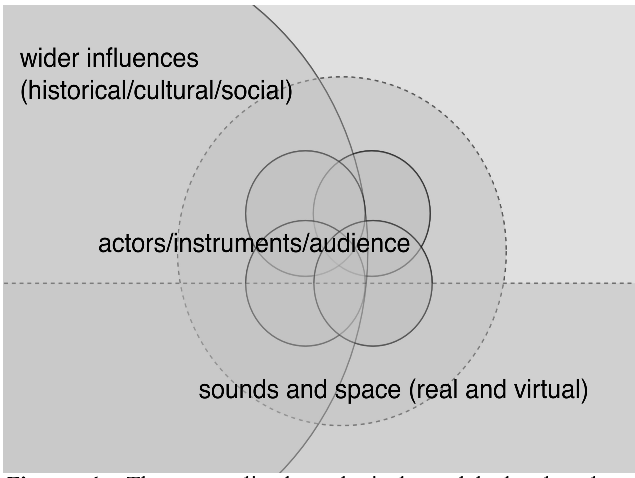

Figure 1: The generalized ecological model developed and presented in this paper, showing structures of varying scales.

No distinction is made between physical and virtual space, and relationships may cross back and forth between the two.

2.2. Affordances in a Music-Ecological Context

Affordance theory was originally developed by Gibson [37] in the context of perceptual psychology, and pertained to the natural relationships between actors and their environments. The term was subsequently adapted for the field of design by Norman [38], where it referred to the actions made possible by an object's physical form and properties. From this perspective, it is possible to conceive of many traditional musical instruments as particularly complex objects that, while inherently highly specialised, offer a variety of action possibilities. However, in response to the difficulties posed by the intangibility of software, Norman [39] subsequently expanded the concept to include:

- perceived affordances - actions users perceive to be possible
- real affordances - actions that are actually possible.

This notion of perceived affordances is expanded by Gaver [40] to include two additional subcategories:

- sequential affordances - linked in time (i.e. one action reveals subsequent additional action possibilities)
- nested affordances - linked in space (i.e. a combination of affordances reveals a specific associated action).

Both of these concepts are of possible relevance to the musical instrument context. For instance, many established (i.e. acoustic and electric) instrument designs are able to support long-term engagement (i.e. more possibilities are revealed through practice), but also require multiple simultaneous inputs.

We propose that the concept of affordances is a useful addition, or supplement to, the ecological model proposed above (Figure 1). For instance, musical composition can be conceived of as the delineation of a set of productive constraints [41] [42]. Turning this notion around, composition can therefore also be considered as a process by which a set of action possibilities is created. These may be actual or perceived (or rather, enforced, explicitly stated, or implied). This can be readily understood in relation to composition for acoustic instruments. For example, the choice of instrumentation determines, to a significant extent, the palette of sounds that can be employed, and the density of sounds that can be produced simultaneously. If these possibilities also exist in the digital domain, the flexibility of DMIs is such that they are often more loosely or subtly constrained. In both domains, numerous possibilities may exist simultaneously and at a variety of scales, from the micro to the macro and (particularly in ecological approaches) beyond.

This initial ecology of possibilities can (to borrow a painterly analogy) be considered a kind of ground upon which subsequent activity can take place. If in some circumstances this may involve only one participant, collaborative or co-creational activity is commonplace. For instance, a single musical work may involve activities such as composition and re-composition, instrument design, performance, and sound diffusion. It is therefore possible to reframe co-creation as a process by which this initial set of affordances is collaboratively subjected to iterative modification. This process may be more or less protracted, occur sequentially or in parallel, in real-time or non-real-time contexts, or a hybrid of the two.

Clearly, the notion of an ecology implies that multiple groups of affordances may co-exist; what might be considered a distributed and more transient version of Gaver's nested affordances [40]. The relationships between these grouped affordances may vary enormously, from the direct and obvious, to the implied and barely existent. They may also radically change in topology from one moment to the next. This may appear to risk even more fragmentation than the composed instruments model proposed by Wanderley *et al.* [24]. However, if the initial ecology of affordances can be at least partially read and understood, it can provide the basis for a tightly integrated development process. For instance, consider for a moment the affordance lines emerging from each group of affordances as tangible, graspable things (Figure 2). Grabbing and inspecting a handful of affordance lines from several groups at a time may reveal similarities or mutually reinforcing properties. Equally, others may be conflicting or simply unrelated. Thus, the co-creators are cast as privileged selectors gifted with the ability to choose which affordances to draw together and emphasize, and which to downplay.

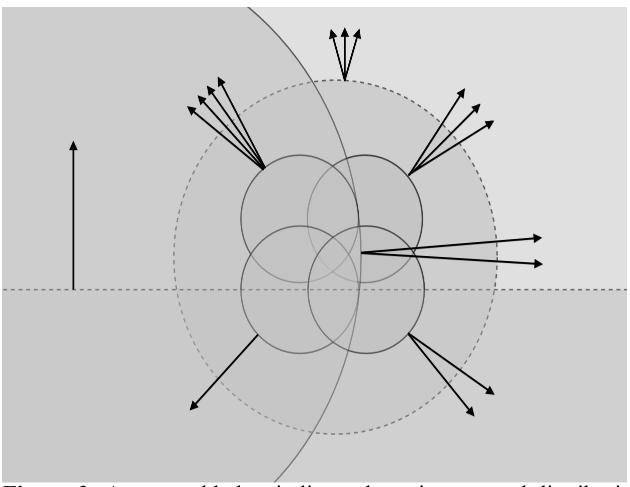

Figure 2: Arrows added to indicate the existance and distribution of affordances within a generic musical ecology.

The ecology of affordances does not distinguish between and is in some ways largely insensitive to traditional distinctions between composition, instrument and performance: any element has the potential to influence any other or others. This can be therefore be closely related to the co-design model proposed by Cook [16], albeit extended beyond the DMI domain to an ecological context.

3. Desire Lines as Example

Desire Lines 3.0 offers an example of the above model in practice. It is a collaborative piece for trumpet, prepared piano (without pianist), and parasitic DMI that feeds upon the sound environment created by the other instruments and audience. *Desire Lines* previously existed in two versions written by Chris Foster for acoustic instruments only; the first for trumpet and piano (without pianist), the second for trumpet and vibraphone (with vibraphonist). In the first version, the relationship between composer and performer is re-imagined from the viewpoint of performer responsibility and how they might manage and control the presentation of material, which has a bearing on the essential character of the composition. In the second, the inclusion of a vibraphone drastically alters the dynamic of that relationship, offering its own comparative analysis of the different ways in which two objects, placed together, can energize one another. In both versions the structure is divided into three parts, punctuated by musical inserts (Figure 3). There are four inserts and the soloist is at liberty to make a selection at will [43].

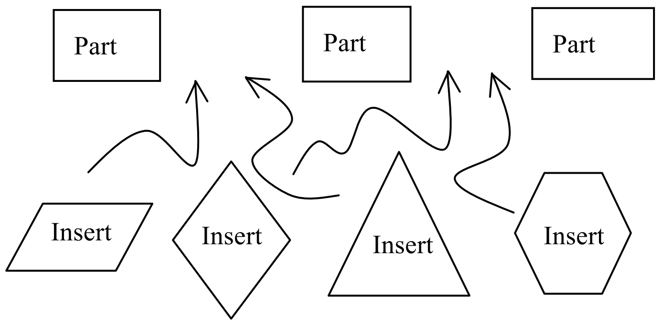

Figure 3: The structure of *Desire Lines*, showing the combinations of parts and inserts.

The first version of *Desire Lines* received its premier in 2012. In early 2014 it was then revived for use as the raw material for collaboration between the authors; an instrument designer, composer, and trumpet player respectively. The prominent affordances of the initial piece include:

- the trumpet has potential to produce a monophonic sound stream only
- chordally tuned sympathetic resonance from prepared piano if stimulated by the acoustic output of the trumpet.
- score implies spatial movement of trumpet bell to direct sound into or away from the interior of the piano.
- the ability of the performer to select different routes (i.e. structure may be different each time the piece is played).
- the trumpet player has only a little spare capacity.

These affordances were then used to inform the design of a new version of the piece that would include a DMI. Early on, it was decided that the DMI would feed on, in parasitic fashion, the local acoustic environment. Thus, the DMI produces no sound of its own and is entirely reliant on the sound produced by the acoustic instruments as well as, to a lesser extent, the sounds of the audience and outside environment.

From there, one of the initial affordances was extended while another was contradicted. First, a live sampling capability was developed in MaxMSP, based on the metaphor of an analogue gate. This gate can be opened and closed by the DMI player via the tilting of a Nintendo Wii Remote controller. In essence, the player is able to capture and store (i.e. sample) sounds from the acoustic environment. The performer can then subsequently recall these sounds, thereby injecting them back into the acoustic environment via a loudspeaker system. This offers the possibility of stacked or layered sounds that the trumpet alone could not produce, and the potential for dialogue between the trumpet player and the DMI player. All captured sounds are stored and catalogued by duration and timbral features at the end of each performance.

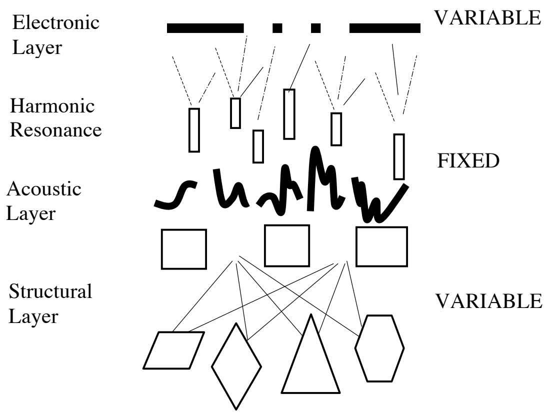

Figure 4: The approximate structure of *Desire Lines 3.0*, showing its various layers (for clarity, not all intersections shown).

Second, the use of a partially open compositional form enables a variety of routes to be taken each time the piece is played (up to 12 possible routes in total). In response to this potential for variation, the MaxMSP patch is modified so that each time live input is captured and stored, there is a randomly determined probability that it will be replaced by a recorded snippet from a previous performance. Thus, 'ghosts' of past performances may be drawn into and appear in the present moment. Based on the audio mosaicing approach outlined by Schwarz and Hackbarth [44], the replacement sound is as closely related to the sound that is to be replaced (in terms of durational and timbral characteristics) as possible. However, if the two sounds (replacement and replaced) are likely to grow more similar as the number of performances increases and therefore more sounds are stored, the two will never be identical. The approximate structure of the resultant piece, *Desire Lines 3.0*, can be seen in Figure 4.

4. Conclusions and Future Work

Desire Lines 3.0 received its premiere in March 2014 at a composition seminar held at the University of Wolverhampton. Its development has revealed a number of issues relating to interdisciplinary collaboration. Most notably, the integration of compositional and acoustic elements into the DMI has helped to blur the previously distinct boundaries between composer, instrument designer and performer. At the very least, it has helped to provide provocative points for discussion and stimulate dialogue that may not have occurred if more established (and therefore culturally ossified) instruments were used. Specifically, if there is a tendency, particularly among composers and performers (i.e. non-designer specialists) to think of established instruments in terms of a set of fixed possibilities that may be utilized for musical purposes, DMIs may encourage non-design specialists to become more actively engaged in the instrument design process. These different perspectives and associated multi-faceted insights are surely useful if DMIs are to become more rounded constructions, able to match or surpass their predecessors on grounds such as expressive subtlety and the potential for long-term engagement.

Equally, the DMI also has implications for performers. On the one hand, it is quite unlike traditional instruments. For example, the performer-instrument interaction is very simple, the sound source is disembodied and unbounded, and the incorporation of chance elements means that outcomes are, to some extent, inherently unrepeatable. Thus, if the relationship between input and output is readily learnable, the performer must accept that its sonic outcomes are never entirely predictable. Thus, it makes little sense to consider mastery of the DMI in terms of conventional criteria such as precision and accuracy, or the degree to which the instrument can be coerced to follow the expressive intention of the performer. This may also apply to other DMIs, particularly those that offer process rather than note-level control or are of a distributed nature. Thus, it may be that acoustic-era models of instrument learning are no longer directly applicable and new, domain-specific models may be required. Even considering DMIs at their most general, acoustic-era models are ill-equipped to consider, for example, the potential for DMIs to be iteratively modified by an individual or community *in parallel to* the learning process, or the possibility of being rendered unmaintainable by layers of technological obsolescence. On the other hand, while the performer-instrument relationship is quite radically altered, some more conventional aspects of performance remain. For example, real-time communication between performers not only remains important, but also still based around sonic and gestural cues. Similarly, the performer-audience relationship also remains intact, albeit with potentially adjusted expectations. Thus, if the technologies underpinning DMIs have widened participation, it may be that these relatively inexperienced participants still have much they could learn about performance craft from players of more traditional instruments.

There are numerous possibilities for future work in relation to the proposed model. Perhaps the most immediate is to explore its use as the basis for an entirely new, bottom-up composition. There is also the potential to explore and incorporate (geographically) distributed online collaboration. For example, entire compositions could be open sourced to enable public development, or physical instruments could be 3-D printed and tested by strangers, whose contributions iteratively improve the basic design.

References

[1] H. Davies: *Creative Explorations of the Glitch in Music*. In *2004 IEEE Conference on the History of Electronics (CHE2004)*. Bletchley Park, 2004.

[2] D. Dunn: *A History of Electronic Music Pioneers*. In W. Vasulka and S. Vasulka (eds.), *Eigenwelt der Apparatewelt: Pioneers of Electronic Art*. Ars Electronica, Linz, 1992.

[3] A. Hunt: *Radical User Interfaces for Real-Time Musical Control.* PhD dissertation, University of York, 1999.

[4] T. Holmes: *Electronic and Experimental Music: Technology, Music and Culture*, pages 3-4. Routledge, New York, 2012.

[5] C. Roads: *Early Electronic Music Instruments: Time Line 1899-1950.* In *Computer Music Journal*, volume 20(3):20–23, 1996.

[6] T. J. Pinch and F. Trocco: *Analog Days: The Invention and Impact of the Moog Synthesizer*. Harvard University Press, Cambridge, 2009.

[7] T. Holmes: *Moog: A History in Recordings*. http://moogfoundation.org/moog-a-history-in-recordings-by-thom-holmes/ (Accessed 26 October 2014).

[8] J. Uechi: *Paul Lansky: Room to Move*. Soundout Archive. http://www.gravitymonkey.com/paul_lansky.html (accessed October 16, 2014).

[9] M. V. Mathews and F. R. Moore: *GROOVE – a program to compose, store, and edit functions of time*. In *Communications of the ACM,* volume 13(12), 1970.

[10] J. Harley: *Xenakis: His Life in Music*, page 115, Routledge, New York, 2004.

[11] M. Waisvisz: *The Hands: A Set of Remote MIDI-Controllers*. In *Proceedings of the 1985 International Computer Music Conference (ICMC'85)*, pages 313–315, 1985.

[12] R. Gehlhaar: *Sound=Space: an interactive musical environment*. In *Contemporary Music Review*, volume 6(1):59–72, 1991.

[13] J. Hochenbaum and A. Kapur: *Towards The Future Practice Room: Empowering Musical Pedagogy through Hyperinstruments*. In *Proceedings of the 2013 International Conference on New Interfaces for Musical Expression (NIME13)*, pages 307–312, 2013.

[14] M. T. Marshall: *Physical Interface Design for Digital Musical Instruments.* Ph.D. dissertation, McGill University, 2008.

[15] P. Rebelo: *Haptic Sensation and Instrumental Transgression*. In *Contemporary Music Review*, volume 25(1-2):27–25, 2006.

[16] P. Cook: *Remutualizing the Musical Instrument: Co-Design of Synthesis Algorithms and Controllers*. In *Journal of New Music Research*, volume 33(3):315–320, 2004.

[17] D. Trueman: *Reinventing the Violin*. Ph.D. thesis, Princeton University, 1999.

[18] D. Robson: *PLAY!: Sound Toys for the Non Musical*. In *Proceedings of the 2001 conference on New Interfaces for Musical Expression (NIME01)*, pages 1–3, 2001.

[19] E. Singer, K. Larke and D. Bianciardi: *LEMUR GuitarBot: MIDI Robotic String Instrument*. In *Proceedings of the 2003 Conference on New Interfaces for Musical Expression (NIME03)*, pages 188–191, 2003.

[20] J. Richards: *32Kg: Performance Systems for a Post-digital Age*. In *Proceedings of the 2006 Conference on New Interfaces for Musical Expression (NIME06)*, pages 283–287, 2006.

[21] S. Jordà: *Digital Lutherie Crafting musical computers for new musics' performance and improvisation*. Ph.D. thesis, Universitat Pompeu Fabra, 2005.

[22] N. Armstrong: *An enactive approach to digital musical instrument design.* Ph.D. thesis, Princeton University, 2006.

[23] N. Moody: *Ashitaka: an audiovisual instrument*. Ph.D. thesis, University of Glasgow, 2009.

[24] M. M. Wanderley, N. Schnell and J. Rovan: *ESCHER-modeling and performing composed instruments in real-time*. In *Proceedings of the 1998 IEEE International Conference on Systems, Man, and Cybernetics (SMC'98)*, 1998.

[25] N. Schnell and M. Battier: *Introducing Composed Instruments: Technical and Musicological Implications.* In *Proceedings of the 2002 Conference on New Interfaces for Musical Expression (NIME02)*, pages 1–5, 2002.

[26] D. Dunn (ed.): *Harry Partch: An Anthology of Critical Perspectives*. Routledge, New York, 2013.

[27] A. Momeni: *Composing instruments: Inventing and performing with generative computer-based instruments*. Ph.D. dissertation, University of California at Berkley, 2005.

[28] D. Holzer: *Schematic as Score: Uses and Abuses of the (In)Deterministic Possibilities of Sound Technology*. In *Vague Terrain 19: Schematic as Score*, 2011.

[29] R. Kuivila and D. Behrman: *Composing with Shifting Sand: A Conversation between Ron Kuivila and David Behrman on Electronic Music and the Ephemerality of Technology*. In *Leonardo Music Journal*, volume 8:13–16, 1998.

[30] J. Driscoll and M. Rogalsky. *David tudor's rainforest: An evolving exploration of resonance*. In *Leonardo Music Journal*, volume 14:25–30, 2004.

[31] M. Gurevich and J. Treviño. *Expression and its discontents: toward an ecology of musical creation*. In *Proceedings of the 2007 international conference on New Interfaces for Musical Expression (NIME07)*, pages 106–111, 2007.

[32] K. Krippendorff: *The Semantic Turn: A New Foundation for Design*. Taylor & Francis, London, 2005.

[33] H. Enquist, K. Tollmar and A. V. Corry: *Interaction Ecologies*. In *Workshop proceedings from the Fifth International Conference on Pervasive Computing*, 2007.

[34] R. Gehlhaar: *Music Technology and Sound Art/Interactivity: Reality Music/Virtual Music*. In the *25th National Conference of the Musicological Society of Australia (MSA)*, 2002.

[35] J. Impett: *Interaction, simulation and invention: a model for interactive music*. In *Proceedings of ALMMA 2001 Workshop on Artificial Models for Musical Applications*, 2001.

[36] M. Grimshaw: *The Acoustic Ecology of the First Person Shooter*. Ph.D. thesis, University of Waikato, 2007.

[37] J. J. Gibson: *The Ecological Approach to Visual Perception*. Houghton Mifflin, Boston, 1979.

[38] D. A. Norman: *The Design of Everyday Things*. Basic Books, New York, 2002.

[39] D.A. Norman: *Affordances, Conventions, and Design*. In *Interactions*, volume 6(3): 38–43, 1999.

[40] W. W. Gaver: *Technological Affordances*. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 79–84, 1991.

[41] M. Henz, S. Lauer and D. Zimmermann: *COMPOzE-intention-based music composition through constraint programming*. In *Proceedings of Tools with Artificial Intelligence*, pages 118–121, 1996.

[42] A. Torsten: *Composing music by composing rules: Design and usage of a generic music constraint system*. Ph.D. dissertation, University of Belfast, 2007.

[43] C. Foster: *Composition Portfolio*. Practice-based Ph.D. dissertation, University of Wolverhampton, 2013.

[44] D. Schwarz and B. Hackbarth: *Navigating variation: composing for audio mosaicing*. In *Procedings of the 2012 International Computer Music Conference (ICMC2012)*, pages 604–607, 2012.